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In 2006, we continued to report substantial progress on "The Production and Study of Antiprotons and Cold Antihydrogen" project funded by AFOSR. Listed below are the publications funded by AFOSR support since March 1,2004.
Publications for 2004. The topics identify the new discoveries and progress.
"Strongly Magnetized Antihydrogen and Its Field Ionization
D. Vrineeanu, B.E. Granger, R. Parrott, H. R. Sadeghpour, L. Cederbaum, A. Mody, J. N. Tan and G. Gabrielse
Phys. Rev. Lett. 92, 133402 (2004).

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FINAL Performance Report
for the period
March 1, 2004 – December 31, 2006

on

The Production and Study of Antiprotons and Cold Antihydrogen

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Phys. Rev. Lett. **92**, 133402 (2004).

"G. Gabrielse, et al. reply" (A reply to a Comment discusses comparing our measured field ionization spectra to theory)
G. Gabrielse, *et al.*
Phys. Rev. Lett. **92**, 149304 (2004).

"Aperture Method to Determine the Density and Geometry of Anti-Particle Plasmas", P. Oxley, N. S.Bowden, R. Parrott, A. Speck, C. Storry, J.N. Tan, M. Wessels, G. Gabrielse, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch and E. A. Hessels
Phys. Lett. B **595**, 60 (2004).

"First Measurement of the Velocity of Slow Antihydrogen Atoms",
G. Gabrielse, A. Speck and C.H. Storry, D. Le Sage, N. Guise, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner, J. Walz, T.W. Haensch, D. Comeau, E.A. Hessels
Phys. Rev. Lett. **93**, 073401 (2004).

"First Evidence for Atoms of Antihydrogen Too Deeply Bound to be Guiding Center Atoms",
G. Gabrielse, A. Speck, C.H. Storry, D. Le Sage, N. Guise, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner, J. Walz, T.W. Haensch, D. Comeau, E.A. Hessels
Submitted for publication.

"Laser-Controlled Production of Rydberg Positronium"
A. Speck, C.H. Storry, E. Hessels and G. Gabrielse
Phys. Lett. B **597**, 257 (2004).

"Slow Antihydrogen",
G. Gabrielse, A. Speck, C.H. Storry, D. Le Sage, N. Guise, P.C. Larochelle, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner, M. Herrmann, J. Walz, T.W. Haensch, D. Comeau, and E.A. Hessels,
In: *Atomic Processes in Plasmas, 14th APS Topical Conference on Atomic Processes in Plasmas*, AIP Conference Proceedings, **730** 3-12 (2004).

Publications for 2005

"Atoms Made Entirely of Antimatter: Two Methods Produce Slow Antihydrogen" (Review Paper)

G. Gabrielse
Adv. At. Mol. Opt. Phys. **50**, 155-217 (2005).

"Laser-Controlled Antihydrogen Production by Two-Stage Charge Exchange",
C.H. Storry, N. Guise, B. Levitt, D. Le Sage, A. Speck, G. Gabrielse, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner, M. Herrmann, J. Walz, T.W. Haensch, D. Comeau, M. George and E.A. Hessels, In: *Low Energy Antiproton Physics, Eighth International Conference on Low Energy Antiproton Physics (LEAP '05)*, edited by D. Grzonka, R. Czyzykiewicz, W. Oelert, R. Rozek and P. Winter, AIP Conference Proceedings, **796** 291-295 (2005).

"ATRAP - Progress Towards Trapped Antihydrogen",
D. Grzonka, D. Comeau, G. Gabrielse, F. Goldenbaum, T.W. Haensch, E.A. Hessels, P. Larochelle, D. Le Sage, B. Levitt, W. Oelert, H. Pittner, T. Sefzick, A. Speck, C.H. Storry, J. Walz and Z. Zhang, In: *Low Energy Antiproton Physics, Eighth International Conference on Low Energy Antiproton Physics (LEAP '05)*, edited by D. Grzonka, R. Czyzykiewicz, W. Oelert, R. Rozek and P. Winter, AIP Conference Proceedings, **796** 296-300 (2005).

Publications for 2006

"Antiproton Mass Measurements"
G. Gabrielse
Int. J. Mass Spectrom. 251, 273-280 (2006).

"Observations of Cold Antihydrogen",
G. Gabrielse,
In: *An Isolated Atomic Particle at Rest in Free Space – A Tribute to Hans Dehmelt, Nobel Laureate*,
Editors: E. Norval Fortson, Ernest M. Henley and Warren G. Nagourney; Alpha Science International Ltd. Oxford, UK (2006) 50-62.

"New Interpretations of Measured Antihydrogen Velocities and Field Ionization Spectra",
T. Pohl, H.R. Sadeghpour and G. Gabrielse,
Phys. Rev. Lett. 97, 143401 (2006).

Thesis Supervised "Two Techniques to Produce Cold Antihydrogen",
Andrew J. Speck, Harvard Ph.D. Thesis (May 23, 2005).

Invited Talks
During the grant period there were a large number of outside lectures that credited AFOSR support.

2004
Jan. 13 Atomic and Molecular Interactions Group (AMIG) of the Institute of Physics, Dublin City University (invited speaker)
Feb. 3 CERN SPSC (antihydrogen progress lecture)
Feb. 11 University of Michigan (physics colloquium)

Feb. 12 University of Michigan (atomic, molecular and optical physics seminar)
Feb. 12 University of Michigan (science and religion lecture)
Mar. 2 University of Uppsala, Sweden (Lecture on attracting students to science and teaching science so they love it)
Mar. 3 University of Uppsala, Sweden (physics seminar)
Mar. 4 Umeå University, Sweden (physics colloquium)
Mar. 4 Umeå University, Sweden (atomic physics seminar)
Mar. 9 Göteborg University, Sweden (physics colloquium)
Mar. 9 Göteborg University, Sweden (Lecture on attracting students to science and teaching science so they love it)
Mar. 10 Manne Sigbahn Laboratory, Stockholm (physics colloquium)
Mar. 11 University of Stockholm, Sweden (Alba Nova colloquium)

Mar. 12 Uppsala University, Sweden (physics colloquium)
Apr. 19 14th American Physical Society Topical Conference on Atomic Processes in Plasmas (APiP), Santa Fe, NM (the plenary lecture)
Apr. 22 Pluecker Lecture I, University of Bonn (physics colloquium)
Apr. 23 Pluecker Lecture II, University of Bonn (special audience lecture)
May 7 KVA Seminar, Groningen, The Netherlands
May 10 Free University of Amsterdam (physics colloquium)
May 13 Eindhoven University (physics colloquium)
May 14 Nijmegen Univeristy (physics colloquium)
May 15 US National Academy of Sciences CAMOS (invited lecture)
May 17 Aachen University (physics colloquium)
May 18 Johannes Gutenberg University and Max Planck Institute for Polymer Research, Mainz, Germany (physics colloquium)
May 24 University of Nottingham, UK (physics colloquium)
May 26 University of Sussex, UK (physics colloquium)
May 28 University of Liverpool, UK (particle physics seminar)
July 27 XIX International Conference on Atomic Physics, Rio de Janeiro (invited speaker)
Aug. 25 Laser Spectroscopy Conference, Novosibirsk, Russia (invited speaker)
Sept. 24 SPSC Meeting on a Future Fixed Target Programme at CERN, Villars, Switzerland (invited lecture)
Oct. 14 Calvin College (physics colloquium)
Nov. 16 Guelph-Waterloo Physics Institute, Guelph, Ontario (distinguished scientist lecture)
Dec. 2 California Institute of Technology (physics colloquium)
Dec. 3 California State University, Long Beach (physics colloquium)
Dec. 9 Wesleyan University (physics colloquium)
Dec. 14 MIT/Harvard Center for Ultracold Atoms seminar
Dec. 16 Brookhaven National Laboratory (particle physics seminar)

2005

Jan. 21 Ohio University (physics colloquium)
Jan. 27 Yale University (Hanan Rosenthal Memorial Lecture)
Jan. 28 Yale University (physics colloquium)
Feb. 4 University of Connecticut (physics colloquium)

Feb. 14 Harvard University (physics colloquium)
Feb. 24 International Conference on Exotic Atoms (EXA 2005), Vienna, Austria (invited lecture)
Mar. 7 Atomic High-Precision Mass Spectroscopy Symposium (SYAM), 69th Annual Meeting of the German Physical Society, Berlin (invited lecture)
Mar. 18 University of Virginia (graduate recruitment lecture)
Mar. 24 60th Annual Meeting of the Physical Society of Japan, Noda, Japan (invited lecture)
Mar. 30 University of Wisconsin, Madison (physics colloquium)
Apr. 22 Dunbar High School, Baltimore, MD (lectures to science classes)
May 10 Stanford University (physics colloquium)
May 20 International Conference of Low Energy Antiproton Physics (LEAP 2005), Bonn, Germany (special "Year of Einstein" invited lecture)
July 28 XIII International Workshop on Low Energy Positron and Positronium Physics, Campinas, Brazil (plenary lecture)
Aug. 6 Conference of the European Group for Atomic Systems (EGAS 37), Dublin City University (plenary lecture)
Sep. 22 Dordt College, Sioux City, IA (public lecture)
Sept. 23 Dordt College, Sioux City, IA (lecture for science majors)
Sept. 27 Cold and Ultracold Plasma and Rydberg Physics Workshop, Institute for Theoretical Atomic, Molecular and Optical Physics, Harvard (invited lecture)
Oct. 8 Charles H. Townes Celebration, University of California, Berkeley (panelist)
Oct. 28 50th Anniversary of the Discovery of the Antiproton Symposium, Lawrence Berkeley National Laboratory (invited lecture)
Nov. 15 Aachen University of Technology, Germany (physics colloquium)
Dec. 13 GSI, Darmstadt, Germany (physics colloquium)

2006

Jan. 24 CERN SPSC, Geneva, Switzerland
Jan. 27 Brookhaven National Laboratory (magnet group seminar)
Feb. 9 University of Illinois (physics colloquium)
Feb. 21 University of Grűnberg, European Graduate School Lecture Week, Germany (antihydrogen lecture)
Feb. 22 University of Grűnberg, European Graduate School Lecture Week, Germany (electron magnetic moment lecture)
Feb. 23 University of Grűnberg, European Graduate School Lecture Week, Germany (helium spectroscopy lecture)
Mar. 1 University of Cambridge, UK (physics colloquium)
Mar. 2 University of Cambridge, UK (Faraday Lecture in Science and Religion)
Mar. 2 Grant Writing for Non-native English Speakers, Boston, MA
Apr. 7 Cultivating Inquiry Workshop, Lexington, MA (keynote address to 150 high school teachers)
Apr. 20 Dunbar High School, Baltimore, MD (lectures to science classes)
May 16 Division of Atomic, Molecular and Optical Physics (DAMOP), Knoxville, TN (invited lecture for graduate student symposium)
May 19 Calvin College (distinguished alumnus talks to faculty, boards and at commencement)

June 2 CIPANP Conference on the Intersections of Particle and Nuclear Physics (invited lecture), Puerto Rico (invited lecture)
June 19 Lepton Moments 2006, Cape Cod, MA (invited speaker)
July 20 International Conference on Atomic Physics (ICAP 2006), Innsbruck, Austria (invited speaker)
July 25 International Conference on Atomic Collisions in Solids (ICACS 2006), Berlin (special invited lecture)
Sept. 5 Trapped Charged Particles and Fundamental Physics Conference, Vancouver, Canada (invited lecture)
Sept. 15 National Institute of Standards and Technology, Gaithersburg (physics colloquium)
Sept. 18 Harvard University (physics colloquium)
Sept. 19 Center for Ultracold Atoms, MIT (seminar)
Oct. 10 Flavour in the Era of the LHC, CERN, Geneva (invited lecture)
Oct. 27 Conference on the Applications of Gamma Ray Diffraction, Grenoble, France (invited lecture)
Oct. 31 American Physical Society, Division of Plasma Physics, Philadelphia (invited tutorial)
Nov. 13 University of Washington, Seattle (physics colloquium)
Nov. 15 Rutgers University (physics colloquium)
Nov. 16 Princeton University (physics colloquium)
Dec. 7 University of Oklahoma, Norman (physics colloquium)
Dec. 8 Argonne National Laboratory (physics colloquium)

New Inventions and Patents: None

Honors/Awards:

George Ledlie Prize, Harvard University, 2004. The Ledlie Prize is awarded approximately every two years to "the person at the University who has by research, discovery or otherwise made the most valuable contribution to science, or in any way for the benefit of mankind."

Some quotations from http://www.hno.harvard.edu/gazette/2004/04.22/03-ledlie.html are listed below:

"He received the award for his 'stunning' scientific accomplishment of creating antimatter, according to Provost Steven Hyman."

"As the head of an international team of physicists at CERN [European Organization for Nuclear Research], Professor Gabrielse developed the techniques to accumulate antiprotons at energies more than 10^{10} times lower than previously realized," Hyman said. These techniques allow for extremely accurate measurements of the properties of matter and antimatter."

"Gerald Gabrielse's achievements in pushing back the frontiers of knowledge are nothing less than extraordinary," said Harvard President Lawrence H. Summers. "His work not only throws light on some of the fundamental questions about the nature of matter, but has also led to several technological advances in other fields, such as medicine."

"In recommending Gabrielse for the award, FAS Dean William C. Kirby explained that the goal of his experiments is to "ultimately help to solve puzzles about antimatter's presence in the universe. The spin-off technology associated with this work has been a benefit in its own

right, helping advance nuclear magnetic resonance, and magnetic resonance imaging techniques."

Alexander von Humboldt Research Award, 2005 for a project entitled "Fundamental Studies of Cold Antiprotons and Antihydrogen". For more information on the award, please go to the website: http://www.avh.de/en/programme/preise/pt.htm.

Distinguished Alumni Award, Calvin College 2006. "He and the international team that he leads are known for developing ways to cool and manipulate extremely cold antimatter particles and for making cold antihydrogen atoms. His Harvard research team tests some of the fundamental laws of nature with extremely accurate measurements of the properties of single electrons and antiprotons and with laser spectroscopy." For additional information on Calvin College Distinguished Alumni Award, please visit their website at: http://www.calvin.edu/alumni/board/daa.htm.